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Aerobic endurance and physiological thresholds estimated from submaximal heart-rate kinetics: comparison with cardiopulmonary exercise and sprint testing

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Abstract

Purpose Cardiopulmonary exercise testing (CPET) defines individual training intensities but requires a laboratory and maximal effort. We assessed whether the TrueZone model (TZM) can estimate CPET outcomes, maximum sprint speed, and a model-defined endurance parameter (E) from one submaximal running and recovery test.

Methods Forty-five adults (26 men, 19 women) performed a submaximal treadmill test; 38 also completed CPET and 43 a 50-m sprint test. TZM estimates of ventilatory threshold speeds (VT_1 , VT_2), VO_{2max} , HR_{max} , and maximum speed were compared with measured values and with simple benchmarks: each speed as a fixed cohort-average multiple of the test pace, and age-predicted HR_{max} . E was compared with a reference value (E_r) calculated from measured sprint and VT_2 speeds.

Results VT_1 and VT_2 speeds tracked CPET ($R^2 = 0.97$ and 0.94 ; MAE 0.24 and 0.49 $km \cdot h^{-1}$). The pace benchmark came close for VT_2 (MAE 0.63 $km \cdot h^{-1}$) but not for VT_1 (0.47 $km \cdot h^{-1}$) or maximum speed (2.81 vs 0.40 $km \cdot h^{-1}$). Estimated HR_{max} exceeded CPET HR_{peak} by 3.77 bpm (MAE 3.99 bpm; age-predicted 7.76 bpm). VO_{2max} estimated from model speed at VO_{2max} had an MAE of 2.60 $mL \cdot kg^{-1} \cdot min^{-1}$ ($R^2 = 0.86$). E was strongly associated with E_r ($r = 0.91$; mean difference -0.015), although E_r spanned a wider range.

Conclusions From one submaximal test, TZM closely estimated ventilatory thresholds, VO_{2max} , HR_{max} , and maximum sprint speed. Its advantage over pace-based estimates was small near the tested intensity and grew for outcomes further from it. E is a candidate endurance measure requiring independent physiological validation.

Keywords: aerobic endurance · heart-rate kinetics · submaximal exercise testing · ventilatory thresholds · maximal oxygen uptake · maximum sprint speed

30 Abbreviations and symbols

CPET	Cardiopulmonary exercise testing
E	TZM-derived endurance parameter
E_r	Endurance value calculated from VT_2 speed and max sprint speed
$HR_{\max}$	Maximum heart rate; estimated by TZM in this study
HR_{peak}	Highest heart rate recorded during CPET
LoA	Limits of agreement
MAE	Mean absolute error
P	TZM heart-rate scale
$P_{1.5}, P_2$	Model-derived heart rates corresponding to VT_1 and VT_2
RHR	Resting heart rate
RMSE	Root mean square error
TZM	TrueZone model
V	TZM normalized intensity scale
V_0	Lower intercept of the TZM intensity scale
$V_{1.5}, V_2$	Model intensity landmarks corresponding to VT_1 and VT_2
V_3	Model intensity landmark corresponding to speed at $VO_{2\max}$
$V_{\max}$	TZM-derived maximum running speed
VO_2	Oxygen uptake
$VO_{2\max}$	Maximal oxygen uptake
VT_1	First ventilatory threshold
VT_2	Second ventilatory threshold
$vVO_{2\max}$	Running speed at $VO_{2\max}$
Z_0-Z_6	Individualized TZM intensity- and heart rate zones

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Introduction

Aerobic endurance has no universally accepted single measure and is commonly characterized through physiological thresholds, maximal aerobic capacity, and performance across exercise durations (Zakynthinaki 2015; Emig and Peltonen 2020). Maximal oxygen uptake ($\text{VO}_{2\text{max}}$) is a major determinant of aerobic capacity, but it does not fully explain differences in endurance performance among individuals with similar $\text{VO}_{2\text{max}}$ (Joyner and Coyle 2008; Larsen and Sheel 2015). Performance also depends on running economy and the fraction of maximal aerobic capacity that can be sustained, commonly characterized using lactate or ventilatory thresholds (Joyner and Coyle 2008; Mougin et al. 2026). Physiological resilience, the ability to preserve these physiological characteristics as fatigue accumulates, has recently been proposed as an additional determinant of endurance performance (Jones 2024; Jones and Kirby 2025).

Threshold definitions also vary, encompassing lactate and ventilatory thresholds, critical power, and maximal metabolic steady state, whose correspondence remains debated (Faude et al. 2009; Jones et al. 2019; Poole et al. 2021; Dotan 2022; Caen et al. 2024). Nevertheless, threshold position provides information beyond $\text{VO}_{2\text{max}}$. Recent evidence suggests that metabolic phenotype contributes to this position: maximal glycolytic flux has been associated with metabolic thresholds independently of $\text{VO}_{2\text{max}}$ (Meixner et al. 2026), while maximal lactate accumulation rate has been proposed as a complementary descriptor of oxidative–glycolytic characteristics (Quittmann 2026). Thus, runners with similar aerobic capacities may differ in both sustainable intensity and their reserve above it. This motivates an endurance measure relating to threshold, maximal aerobic, and sprint capacities.

Heart rate provides a practical basis for repeated assessment because it can be recorded continuously during exercise and recovery with relatively little burden. Heart-rate kinetics have previously been used to model exercise responses and endurance-related performance (Zakynthinaki 2015; Mazzoleni et al. 2016), while assigning thresholds from fixed percentages of HR_{max} , $\text{VO}_{2\text{max}}$, or running speed can produce substantial individual error (Nuuttila et al. 2025). The TrueZone heart rate kinetics model (TZM) estimates an individual's intensity scale from heart rate and speed during submaximal running and recovery, without a maximal test. From this scale it locates and aligns thresholds in heart rate and speed, and predicts maximal heart rate, maximal aerobic speed and maximal sprint speed, all governed by a single endurance parameter, E . We tested each estimate against independently measured CPET and sprint outcomes and tested whether E relates to those outcomes as the model predicts.

The aim of this study was to evaluate whether a heart-rate kinetics model (TZM) could estimate physiological thresholds, maximal aerobic variables, and maximum running speed from a single submaximal exercise and recovery profile. The study addressed three research questions: (1) Can a single submaximal exercise and recovery test provide estimates of ventilatory thresholds, $\text{VO}_{2\text{max}}$, and HR_{max} that agree with independent CPET measurements? (2) Can maximum sprint speed be estimated from a submaximal exercise and recovery test? (3) Does model-derived endurance (E) agree with a value calculated from independently measured VT_2 and maximum sprint speed?

Methods

Experiment design

The study comprised three tests performed on separate days: a submaximal treadmill run, a 50-m sprint test, and incremental cardiopulmonary exercise testing (CPET). Forty-five individuals (26 men, 19 women), aged 25–60 years and spanning a broad

range of recreational to national-level running training backgrounds, were recruited via social media. Exclusion criteria were known heart disease or hypertension. Height, body mass and body mass index were recorded before testing. All participants provided written informed consent before participation. The study was approved by the Icelandic Bioethics Committee (VSN-24-004).

Submaximal running test

Participants wore two heart-rate monitors (Polar H7 chest strap and a Polar Verity Sense armband, as a back-up device (both Polar Electro Oy, Kempele, Finland)). Testing was performed on a Woodway treadmill (Woodway USA, Inc., Waukesha, WI, USA) at 1% incline and comprised a 3-min warm-up, 2-min rest, 20-min run at a self-selected pace estimated to be sustainable for 40–60 min, and 10-min supine recovery. Rating of perceived exertion was recorded every 5 min using the 20-point Borg scale (Borg 1982). Heart rate was recorded continuously throughout exercise and recovery. Participants could stop at any time; 40 of them completed the full run, while five stopped early. Heart rate data were continuously recorded from both devices.

Sprint test

The sprint test was performed at least two weeks after the submaximal test on an indoor track using Witty Pro infrared timing gates (Microgate Srl, Bolzano, Italy) positioned at 10-m intervals from 0 to 50 m. Following a standardized 20-min warm-up, participants completed up to three maximal 50-m sprints from a standing start, with at least 5 min recovery between attempts. Split times were recorded electronically at each 10-m interval and used to determine maximum sprint speed. The maximum sprinting speed was determined as the average of the two fastest 10-m splits from the fastest attempt.

Cardiopulmonary exercise test

CPET was performed at least two weeks after the sprint test using the same treadmill and a Vyntus CPX metabolic system (Vyaire Medical GmbH, Höchberg, Germany). Before each CPET, gas analyzers were calibrated using ambient air and a certified gas mixture (80% N₂, 15% O₂, 5% CO₂), Flow/volume calibration used an integrated blower, and gas-signal timing was automatically aligned with the volume signal. Breath-by-breath data were smoothed using an eight-breath moving average.

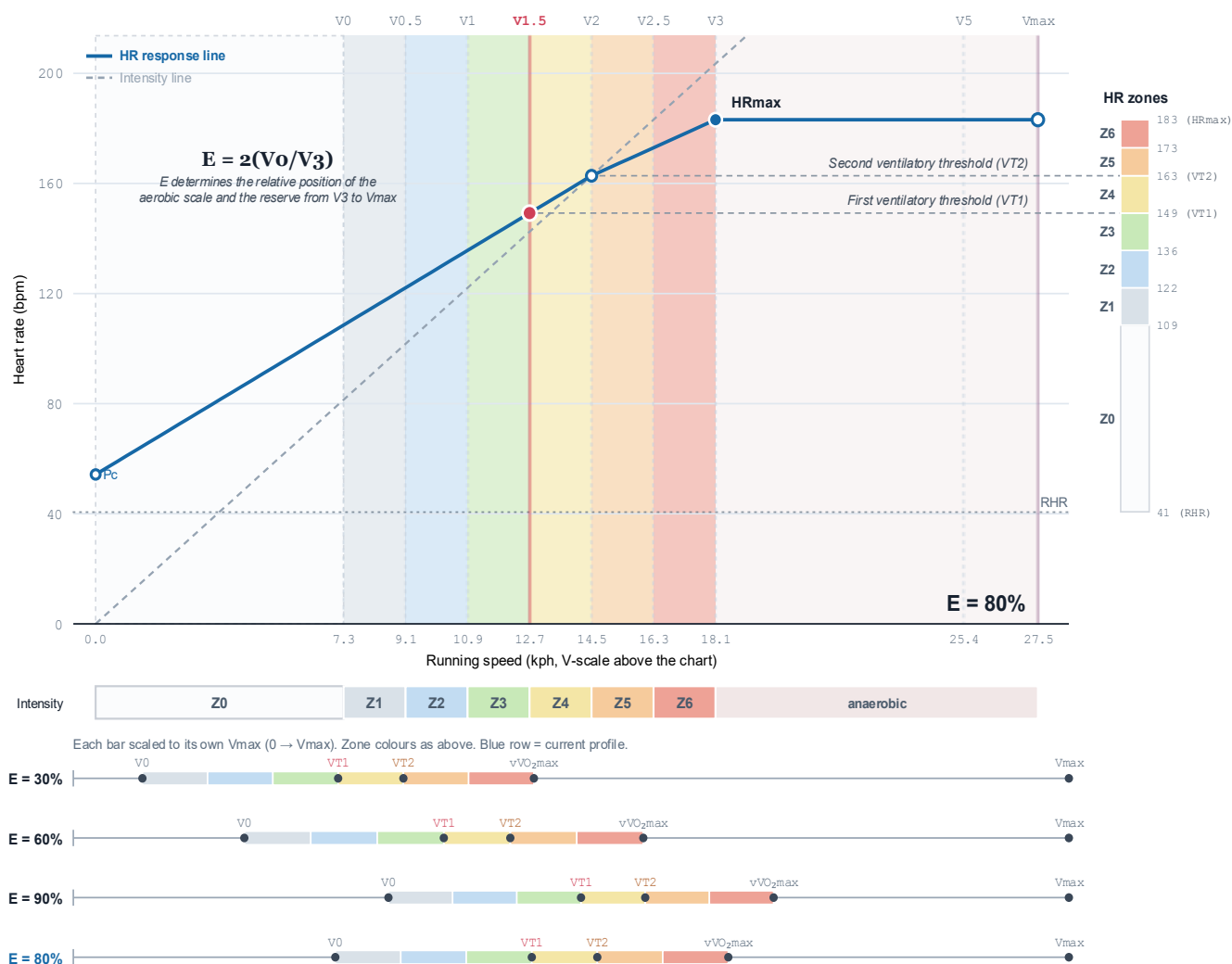
Five individualized incremental protocols were used to accommodate differences in fitness. All protocols used 1-min stages at 1% incline, with starting speeds of 8–12 km·h⁻¹ and increments of 0.5–0.9 km·h⁻¹·min⁻¹, selected to produce exhaustion within approximately 10–14 min. Each test was preceded by a 5-min jog and followed by 5 min seated recovery. Heart rate and breath-by-breath gas exchange were recorded throughout, with heart rate recorded using the same two monitors as above.

Ventilatory thresholds were identified using multiple gas-exchange criteria (Online Resource 1, Fig. S1). VT₁ was determined from the first systematic increase in ventilatory equivalent for oxygen and associated gas-exchange responses, and VT₂ from the onset of respiratory compensation. Automated breakpoint detection in SentrySuite (Vyntus CPX 2019) was reviewed post hoc and adjusted where necessary using the combined ventilatory-equivalent and end-tidal gas responses. The corresponding running speeds and heart rates were retained as VT₁v, VT₂v, VT₁HR, and VT₂HR for comparison with model-derived values (Binder et al. 2008).

Model framework and definition of endurance

The TZM uses aligned intensity (V) and heart rate (P) scales defined by evenly spaced normalized thresholds from V₀ to V₃ (Fig. 1). The V-scale represents increasing exercise intensity, while the corresponding P-scale describes the individualized

103 heart-rate positions of the same model thresholds. Within the framework, $V_{1.5}$ is aligned with VT_1 , V_2 with VT_2 , and V_3 with
 104 velocity at VO_{2max} (vVO_{2max}). Maximum running speed (V_{max}) extends beyond V_3 .



105

106 **Fig. 1.** The TrueZone individualized intensity and heart-rate framework. Illustrative example for $E = 80\%$. Horizontal axis: running speed
 107 with thresholds V_0 – V_3 (shown above), individualized zones Z_0 – Z_6 and maximum speed (V_{max}), zone key shown below. Vertical axis: heart
 108 rate (RHR to HR_{max}) with the zone key at right. $V_{1.5}$, V_2 and V_3 align with VT_1 , VT_2 and vVO_{2max} . Lines show the modelled heart-rate
 109 response (solid) and the normalized intensity (dashed). The scales below show the aerobic zones Z_1 – Z_6 colored as above for $E = 30\%$, 60% ,
 110 90% , and 80% , normalized from rest to V_{max} (fixed at right). As E rises, thresholds slide toward V_{max} , the Z_0 base widens, and the anaerobic
 111 reserve ($vVO_{2max} \rightarrow V_{max}$) narrows.

112 The TZM framework can be interpreted as a normalized physiological continuum across which the relative contributions of
 113 oxidative and glycolytic processes change with increasing intensity. The threshold positions are therefore model-defined
 114 landmarks rather than direct measurements of muscle-fiber recruitment. This distinction is important because muscle
 115 recruitment was not measured in the present study. The model structure was developed before this study. Three choices were
 116 informed by the present data: the alignment of VT_1 with $V_{1.5}$ rather than V_1 , the endurance-dependent extension from V_5 to

$V_{\max}$, and the running-cost constant used to convert V_3 to $VO_{2\max}$ (the cohort mean running economy). No coefficient was estimated by regression on these data, but the VT_1 , maximum-speed, and $VO_{2\max}$ comparisons should be regarded as partly in-sample until replicated.

The same threshold structure is projected onto the heart-rate scale. Heart rate rises from resting values toward $HR_{\max}$, with the P-scale offset from the V-scale rather than expressed as fixed percentages of $HR_{\max}$. The range below V_3 is divided into six individualized zones (Z_1 – Z_6) above a base zone (Z_0). Aerobic endurance (E ; 0–1) is defined geometrically as

$$E = 2 \cdot V_0/V_3$$

Thus, E determines the relative position of the lower intensity intercept and the spacing of the individualized intensity scale. Higher E corresponds to a relatively higher V_0 and a smaller reserve between threshold intensity and maximum running speed.

Model analysis of submaximal test data

Heart rate and treadmill-speed data from the submaximal test were analyzed using a physiologically structured heart-rate kinetics model (TZM) incorporating the exercise response, slow heart-rate drift, and recovery (Online Resource 3). The drift component is a model construct analogous to the VO_2 slow component, whose mechanism remains debated: slow-component magnitude correlates with lactate-estimated glycolytic contribution (Shaw et al. 2026), yet lactate accumulation itself appears not to be causal (Taboni et al. 2025), and a declining glycolytic rate with compensatory oxidative supply has been proposed (Rothschild et al. 2026). Three core parameters — $HR_{\max}$, exercise intensity (V), and endurance (E) — were fitted jointly by minimizing residual error between observed and modelled heart rate across both exercise and recovery. In 23 of the 44 participants, the drift-scaling factor ϕ was additionally adjusted from its default to match a blunted heart-rate drift during exercise; all other model constants were fixed and identical for all participants (Online Resource 3).

From the fitted scales, threshold speeds and heart rates were obtained at $V_{1.5}$ (VT_1 -equivalent), V_2 (VT_2 -equivalent), and V_3 ($vVO_{2\max}$ -equivalent). $VO_{2\max}$ was estimated as V_3 multiplied by a fixed energy cost of running of $3.09 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \text{ per km} \cdot \text{h}^{-1}$, corresponding to the cohort mean running economy measured during CPET ($185.6 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$, $n = 34$). Maximum running speed was extrapolated beyond V_3 according to the endurance-dependent V-scale geometry described in Online Resource 3. Treadmill speeds were converted to equivalent level overground speeds to account for the 1% treadmill incline and absence of air resistance (Online Resource 1).

External construct validation of endurance

Because no established reference measure of E exists, an external endurance estimate (E_r) was calculated from measurements independent of the submaximal model fit: maximum sprint speed and CPET-derived VT_2 speed. Their ratio was defined as

$$Rind = V_{\max}/VT_2v$$

The model geometry specifies a closed-form relationship between E and the $V_{\max}/V_2$ ratio (Table S5). Accordingly,

$$Er = (Rind + 11 - \sqrt{(Rind - 1)(Rind + 71)})/6$$

No coefficients in this transformation were fitted to the present validation data. Because neither sprint-derived $V_{\max}$ nor CPET-derived VT_2 was used to estimate E from the submaximal heart-rate profile, comparison of E_r with model-derived E provided an external test of the predicted relationship among endurance, threshold speed, and maximum sprint speed.

Statistics

Statistical analyses were performed in jamovi v2.6.44 (The jamovi project 2025). The sample size was calculated for paired mean differences ($d = 0.5$, $\alpha = 0.05$, power = 0.80; minimum $n = 34$), not for the precision of agreement estimates, so agreement was interpreted from bias, MAE, and 95% limits of agreement. Sex differences were assessed using independent-samples t -tests. Paired-samples t -tests compared model-derived variables with their CPET- or sprint-derived reference measures. Associations and agreement were assessed using Pearson correlation, linear regression, and Bland–Altman analysis. Regression slopes were tested against 1.0 and intercepts against zero. Agreement statistics included mean bias, mean absolute error (MAE), root mean square error (RMSE), and 95% limits of agreement. Proportional and constant bias were assessed with Deming regression (error-variance ratio 1) and Passing–Bablok regression (Passing and Bablok 1983) using the SimplyAgree module (Caldwell 2022) in jamovi. Statistical significance was set at $p < 0.05$.

Naive benchmarks were computed for comparison with TZM in the same participants. Threshold and maximum speeds were predicted as the self-selected submaximal running pace multiplied by a single cohort constant k , the mean individual ratio of reference speed to pace ($k = 1.007$ for VT_2 , 0.877 for VT_1 , and 2.202 for maximum sprint speed). $HR_{\max}$ was predicted from age as $208 - 0.7 \times \text{age}$ (Tanaka et al. 2001). The association between E and the individual ratio of maximum sprint speed to running pace was assessed by Pearson correlation. Absolute errors of participants fitted with an adjusted drift-scaling factor ϕ ($n = 23$) and with the default ($n = 21$) were compared with Mann–Whitney U tests.

Generative AI statement

Claude (Anthropic) and ChatGPT (OpenAI) assisted with manuscript drafting, organization, and language revision. Claude also assisted with figure preparation using author-supplied data. All outputs were critically reviewed and verified by the authors, who approved the final manuscript and take full responsibility for its content.

Results

Participant and submaximal test characteristics

All 45 participants completed the submaximal run. One submaximal recording could not be fitted because of a treadmill failure after 5 min, leaving 44 model profiles. Seven participants did not attend CPET, leaving 38 for $VO_{2\max}$ and $vVO_{2\max}$; ventilatory thresholds and HR_{peak} could not be determined in one further test ($n = 37$). Two participants did not complete the sprint test ($n = 43$), giving 42 paired maximum-speed comparisons. The five participants who stopped the submaximal run early had completed more than 10 min of running followed by the full 10-min recovery, which is sufficient for model fitting, and were retained. Participant characteristics and submaximal test conditions are summarized in Table 1. Mean running speed was $10.84 \pm 1.32 \text{ km} \cdot \text{h}^{-1}$ in women and $12.57 \pm 2.36 \text{ km} \cdot \text{h}^{-1}$ in men. Mean perceived exertion was similar between groups, at 13.74 ± 1.98 and 13.96 ± 2.15 , respectively, on the Borg 6–20 scale.

Comparison with CPET outcomes

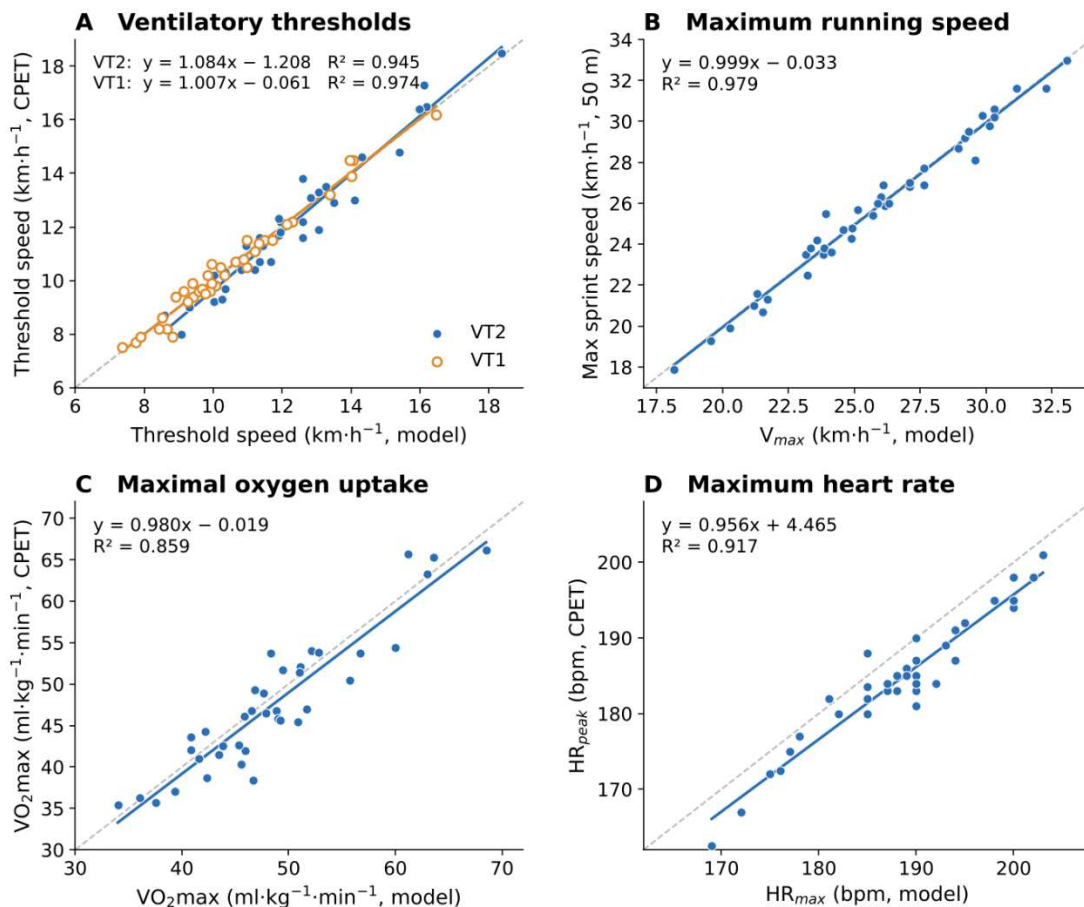
Model-derived VT_1 and VT_2 running speeds were strongly associated with their CPET-derived counterparts ($R^2 = 0.97$ and 0.94 , respectively; Fig. 2A). Mean reference-minus-model differences were $0.01 \text{ km} \cdot \text{h}^{-1}$ for VT_1 and $-0.17 \text{ km} \cdot \text{h}^{-1}$ for VT_2 . Mean absolute errors were 0.24 and $0.49 \text{ km} \cdot \text{h}^{-1}$, respectively (Table 2). The corresponding 95% limits of agreement were -0.64 to $0.65 \text{ km} \cdot \text{h}^{-1}$ for VT_1 and -1.34 to $0.99 \text{ km} \cdot \text{h}^{-1}$ for VT_2 (Fig. 3). VT_2 speed showed a small proportional bias ($p = 0.009$; regression slope 1.08), the model slightly compressing the range of CPET VT_2 . Model-derived threshold heart rates also

187 tracked CPET measurements, although their associations were weaker than those for threshold speeds ($R^2 = 0.72$ for VT_1 and
 188 0.81 for VT_2). Mean absolute errors were 3.39 and 3.01 bpm, respectively (Table 2). Additional CPET characteristics are
 189 provided in Online Resource 2, Table S2.

190 **Table 1** Participant characteristics (women, $n = 19$ and men, $n = 26$) and submaximal test conditions.

Characteristic	Women, mean $\pm$ SD	Men, mean $\pm$ SD
Age (years)	40.1 $\pm$ 7.7	38.9 $\pm$ 8.3
Height (cm)	164.1 $\pm$ 6.9	182.2 $\pm$ 5.0
Body mass (kg)	63.1 $\pm$ 8.0	85.7 $\pm$ 12.1
BMI ($\text{kg}\cdot\text{m}^{-2}$)	23.42 $\pm$ 2.75	25.99 $\pm$ 3.80
Submaximal running speed ($\text{km}\cdot\text{h}^{-1}$)	10.84 $\pm$ 1.32	12.57 $\pm$ 2.36
Rating of perceived exertion (Borg)	13.74 $\pm$ 1.98	13.96 $\pm$ 2.15

191 BMI, body mass index; RPE, rating of perceived exertion. Values are mean $\pm$ SD.



192 **Fig. 2** Scatterplots of model estimates versus CPET and sprint measurements. (A) Ventilatory-threshold running speeds — VT_1 (open) and
 193 VT_2 (filled) model estimates versus CPET-determined speeds. (B) Maximum running speed — model $V_{\max}$ versus 50-m sprint-derived
 194 maximum speed. (C) Maximal oxygen uptake estimated from model V_3 ($3.09 \times V_3$) versus CPET. (D) Maximum heart rate versus CPET
 195 HR_{peak} . Dashed line, line of identity; solid line, fitted regression (equation and R^2 inset). $n = 38$ ($VO_{2\max}$), 41 ($V_{\max}$), 37 (thresholds, $HR_{\max}$).
 196

Comparison with maximum sprint speed

Model-derived maximum running speed closely tracked maximum speed measured in the separate 50-m sprint test ($R^2 = 0.98$; Fig. 2B). Mean measured and model-derived speeds were 25.90 and $25.95 \text{ km}\cdot\text{h}^{-1}$, respectively. The mean reference-minus-model difference was $-0.06 \text{ km}\cdot\text{h}^{-1}$, the mean absolute error was $0.40 \text{ km}\cdot\text{h}^{-1}$, and the 95% limits of agreement were -1.08 to $0.97 \text{ km}\cdot\text{h}^{-1}$ (Table 2).

Model V3 corresponded closely with CPET $\dot{V}\text{O}_{2\text{max}}$ ($R^2 = 0.93$, $n = 38$), exceeding it by $0.37 \text{ km}\cdot\text{h}^{-1}$ on average (MAE $0.53 \text{ km}\cdot\text{h}^{-1}$; 95% limits of agreement -1.72 to $0.99 \text{ km}\cdot\text{h}^{-1}$). $\dot{V}\text{O}_{2\text{max}}$ estimated from V3 was strongly associated with CPET $\dot{V}\text{O}_{2\text{max}}$ ($R^2 = 0.86$; Fig. 2C), with a mean difference of $-1.00 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, a mean absolute error of $2.60 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, and 95% limits of agreement of -7.04 to $5.04 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Model-derived HR_{max} was likewise associated with CPET HR_{peak} ($R^2 = 0.92$; Fig. 2D), but CPET HR_{peak} averaged 3.77 bpm below the model estimate. The mean absolute error was 3.99 bpm , and the 95% limits of agreement were -8.58 to 1.04 bpm (Fig. 3). Thus, HR_{max} showed the clearest systematic difference among the CPET comparisons.

Bland–Altman analysis showed small mean biases for most comparisons (Fig. 3). Mean bias was $-1.00 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for $\dot{V}\text{O}_{2\text{max}}$ (95% limits of agreement [LoA], -7.04 to 5.04), $-0.06 \text{ km}\cdot\text{h}^{-1}$ for maximum running speed (-1.08 to 0.97), and $0.01 \text{ km}\cdot\text{h}^{-1}$ for VT1 speed (-0.64 to 0.65). Mean biases for VT1 (not shown) and VT2 heart rate were 0.18 bpm (-7.66 to 8.01) and 1.12 bpm (-6.12 to 8.37), respectively. HR_{max} showed the largest systematic bias, with CPET HR_{peak} averaging 3.77 bpm below model-derived HR_{max} (95% LoA, -8.58 to 1.04 bpm).

Table 2 Agreement of model estimates with independent measurements

Outcome	Paired n	Reference mean $\pm$ SD	Model mean $\pm$ SD	Bias	MAE	95% limits	R^2
VT ₁ speed ($\text{km}\cdot\text{h}^{-1}$)	37	10.51 ± 2.02	10.50 ± 1.98	0.01	0.24	-0.64 to 0.65	0.97
VT ₂ speed ($\text{km}\cdot\text{h}^{-1}$)	37	12.07 ± 2.41	12.25 ± 2.16	-0.17	0.49	-1.34 to 0.99	0.94
VT ₁ heart rate (bpm)	37	150.49 ± 7.40	150.31 ± 6.95	0.18	3.39	-7.66 to 8.01	0.72
VT ₂ heart rate (bpm)	37	166.46 ± 8.39	165.34 ± 7.44	1.12	3.01	-6.12 to 8.37	0.81
$\dot{V}\text{O}_{2\text{max}}$ ($\text{km}\cdot\text{h}^{-1}$)	38	15.33 ± 2.60	15.70 ± 2.51	-0.37	0.53	-1.72 to 0.99	0.93
$\dot{V}\text{O}_{2\text{max}}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	38	47.51 ± 8.19	48.51 ± 7.75	-1.00	2.60	-7.04 to 5.04	0.86
HR _{peak} VS HR _{max} (bpm)	37	184.85 ± 8.40	188.62 ± 8.41	-3.77	3.99	-8.58 to 1.04	0.92
Maximum speed ($\text{km}\cdot\text{h}^{-1}$)	42	25.90 ± 3.62	25.95 ± 3.58	-0.06	0.40	-1.08 to 0.97	0.98
E_r versus E (unitless)	37	0.650 ± 0.132	0.665 ± 0.107	-0.015	0.050	-0.128 to 0.098	0.82

Bias and limits of agreement use reference minus model. MAE is the mean absolute paired difference. Limits are mean paired difference ± 1.96 sample SD of the paired differences. $\dot{V}\text{O}_{2\text{max}}$ is compared with model V₃; model $\dot{V}\text{O}_{2\text{max}} = 3.09 \times V_3$. E_r is calculated using independent VT₂ and sprint measurements but a transformation specified by the TrueZone model; it is not a direct endurance reference.

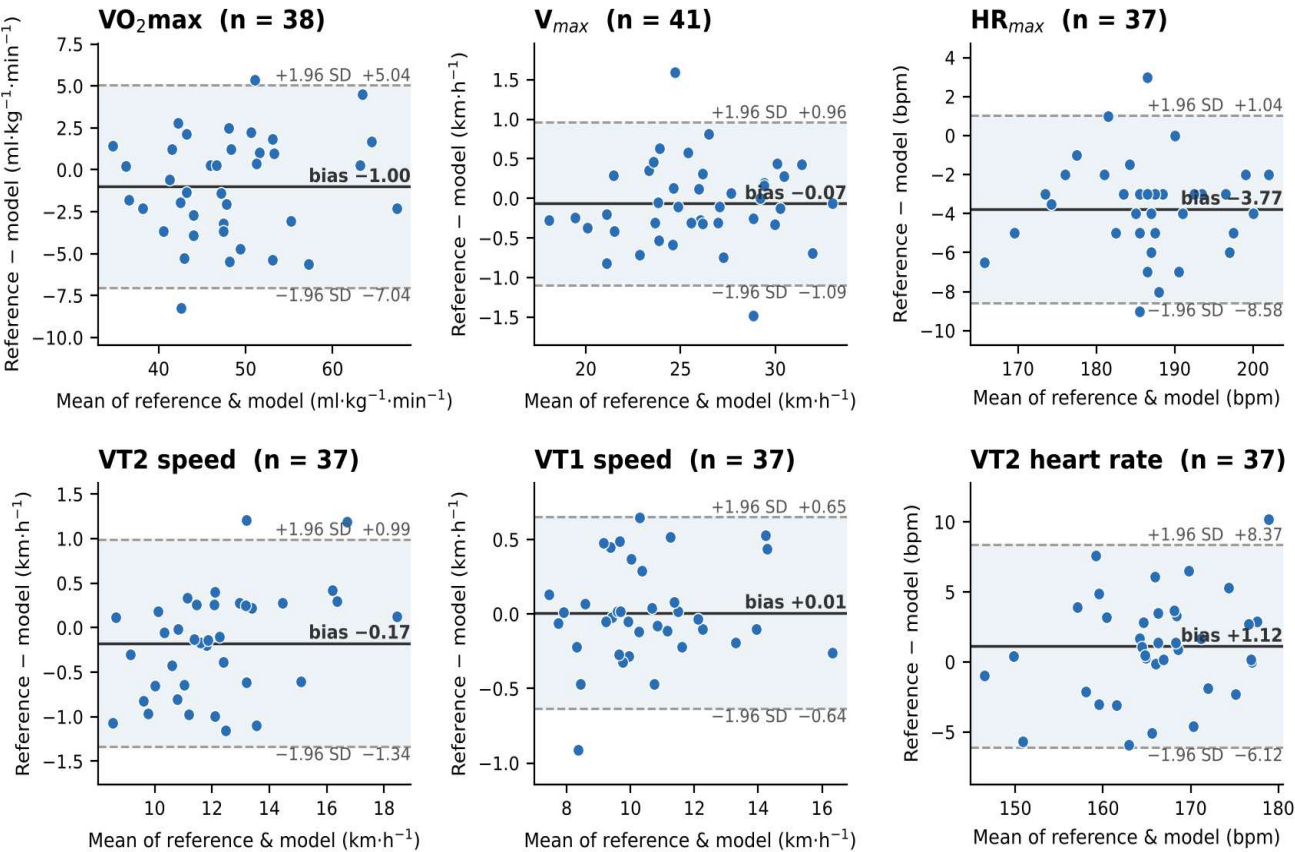


Fig. 3 Bland–Altman plots for CPET and sprint comparisons. $\text{VO}_{2\text{max}}$, maximum speed (V_{max}), maximum heart rate (HR_{max}), VT_2 speed, VT_1 speed, and VT_2 heart rate. Each point represents one participant; the solid line marks the mean bias and dashed lines mark the 95% limits of agreement (bias $\pm$ 1.96 SD).

Comparison with naive benchmarks

Scaling the self-selected pace by a single cohort constant approached TZM for VT_2 speed (MAE 0.63 vs 0.49 $\text{km}\cdot\text{h}^{-1}$), but its error was twice that of TZM for VT_1 speed (0.47 vs 0.24 $\text{km}\cdot\text{h}^{-1}$) and seven times larger for maximum sprint speed (2.81 vs 0.40 $\text{km}\cdot\text{h}^{-1}$; Table 3).

Table 3 Naive benchmarks compared with TZM in the same participants

Outcome	Paired n	Naive benchmark	Naive 95% limits	Naive MAE	TZM MAE	Naive R^2	TZM R^2
VT_2 speed ($\text{km}\cdot\text{h}^{-1}$)	37	$\text{Pace} \times 1.007$	−1.48 to 1.48	0.63	0.49	0.90	0.94
VT_1 speed ($\text{km}\cdot\text{h}^{-1}$)	37	$\text{Pace} \times 0.877$	−1.15 to 1.13	0.47	0.24	0.92	0.97
Maximum speed ($\text{km}\cdot\text{h}^{-1}$)	42	$\text{Pace} \times 2.212$	−7.55 to 6.85	2.81	0.40	0.43	0.98
HR_{max} vs HR_{peak} (bpm)	37	$208 - 0.7 \times \text{age}$	−12.72 to 21.71	7.76	3.99	0.07	0.92

Pace is the self-selected submaximal running pace ($\text{km}\cdot\text{h}^{-1}$); each multiplier k is the cohort mean of the individual ratio of reference speed to pace. HR_{max} benchmark from Tanaka et al. (2001). Limits are reference minus benchmark $\pm$ 1.96 SD.

The pace-based maximum speed also overstated the spread of measured sprint speed (SD 4.84 vs 3.62 km·h⁻¹), producing proportional bias ($p = 0.018$). Age-predicted HR_{max} gave an MAE of 7.76 bpm, compared with 3.99 bpm for TZM. The individual ratio of maximum sprint speed to running pace decreased with E ($r = -0.89$, $R^2 = 0.79$, $p < 0.001$, $n = 42$), closely following the relationship predicted by the model geometry without fitted coefficients.

Correspondence between model-derived and externally calculated endurance

Model-derived endurance (E) was strongly associated with E_r , the value calculated from independently measured CPET VT₂ speed and maximum sprint speed ($r = 0.91$; $R^2 = 0.82$; $n = 37$; Fig. 4A). Mean E was 0.665, compared with 0.650 for E_r . The mean difference ($E_r - E$) was -0.015 , with a mean absolute error of 0.050 and 95% limits of agreement of -0.128 to 0.098 (Table 2; Fig. 4B). E_r is derived from the model's own geometry, so this is construct support, not validation against a gold standard.

The difference between E_r and E varied across their observed range. Regression of paired differences against paired means indicated proportional bias ($p = 0.0048$; Fig. 4B). Deming and Passing–Bablok regression, which allow for error in both estimates, gave consistent slopes of 1.27 (95% CI 1.05 to 1.46) and 1.27 (1.05 to 1.53), with intercepts of -0.19 (-0.32 to -0.05) and -0.20 (-0.35 to -0.05); E_r thus spanned a wider range than E (SD 0.132 vs 0.107), the two estimates coinciding near $E \approx 0.72$. Thus, despite the strong overall association and small mean difference, the two endurance values did not agree equally well across the range.

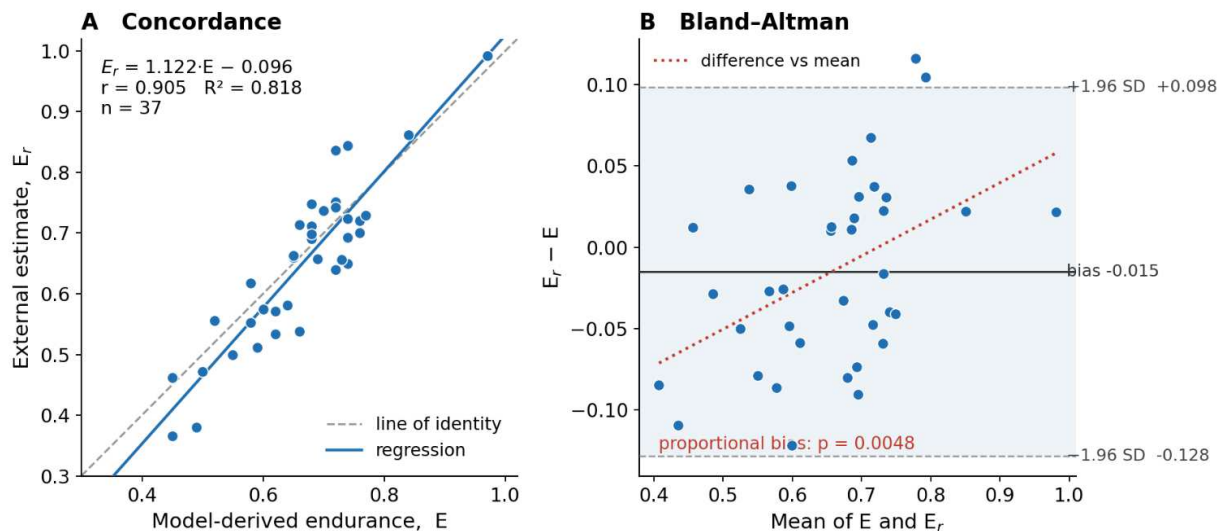


Fig. 4 Construct validation of model-derived endurance (E) against an external estimate (E_r) from independently measured sprint speed and CPET-derived VT₂ ($n = 37$). (A) Concordance: individual participants, line of identity (dashed) and fitted regression ($E_r = 1.122 \cdot E - 0.096$; $r = 0.91$, $R^2 = 0.82$). (B) Bland–Altman: difference ($E_r - E$) versus mean, with mean bias (solid, -0.015) and 95% limits of agreement (dashed, -0.128 to $+0.098$); the dotted line (difference vs mean) indicates proportional bias ($p = 0.0048$).

Absolute errors did not differ between participants fitted with an adjusted drift-scaling factor ϕ ($n = 23$) and with the default ($n = 21$) for any threshold, HR_{max}, VO_{2max}, maximum-speed, or $E - E_r$ comparison (all $p \geq 0.22$); for $v\text{VO}_{2\text{max}}$ the error was smaller in the adjusted group (MAE 0.47 vs 0.61 km·h⁻¹, $p = 0.045$; Online Resource 2, Table S4).

Discussion

Principal findings

A single submaximal running and recovery test allowed the TrueZone model (TZM) to estimate several outcomes conventionally obtained through separate maximal tests. VT_1 and VT_2 speeds showed the closest correspondence with CPET thresholds, while $VO_{2\max}$ and threshold heart rates also showed strong associations but greater individual error. Estimated $HR_{\max}$ tracked CPET HR_{peak} yet was systematically higher. TZM additionally estimated maximum sprint speed with a mean absolute error of $0.40 \text{ km}\cdot\text{h}^{-1}$ against a separate 50-m test, roughly one seventh of the error of a pace-based estimate. Finally, model-derived endurance (E) corresponded closely with the value calculated from independently measured VT_2 and sprint speed, although proportional bias showed that agreement varied across the E range. These findings answer the three research questions at different levels of certainty: correspondence with measured outcomes was strongest for speeds, whereas the E comparison tests a predicted relationship within the model's geometry.

Estimation of CPET outcomes from submaximal heart rate

The close agreement of TZM-derived VT_1 and VT_2 speeds with CPET breakpoints supports individualized threshold placement from the exercise–recovery profile. Mean absolute errors were 0.24 and $0.49 \text{ km}\cdot\text{h}^{-1}$, respectively. This is pertinent because fixed percentages of $HR_{\max}$, $VO_{2\max}$, or running speed can place individuals at appreciably different threshold intensities (Nuuttila et al. 2025). TZM instead fits the individual response and uses its resulting intensity scale to locate both thresholds. Correspondence with ventilatory thresholds should nevertheless be interpreted as such: the present tests do not establish that the TZM landmarks coincide with lactate thresholds or maximal metabolic steady state, which require their own reference measurements (Jones et al. 2019; Caen et al. 2024).

Because the self-selected pace lay close to VT_2 by design, a pace-only estimate approached TZM for VT_2 . Its error doubled for VT_1 and increased roughly sevenfold for maximum sprint speed, whose ratio to threshold speed varies with endurance. TZM's added value therefore lies mainly in locating intensities away from the tested pace, which is the information carried by E . Whether TZM performs equally well when the submaximal run is well below threshold remains to be tested.

$HR_{\max}$ is a particularly demanding extrapolation from a submaximal profile. Although TZM-derived $HR_{\max}$ was strongly associated with CPET HR_{peak} , it exceeded HR_{peak} by 3.77 bpm on average; an age-predicted estimate, by comparison, underestimated HR_{peak} by 4.49 bpm with twice the absolute error (Tanaka et al. 2001). CPET HR_{peak} is the highest value attained in that test rather than a definitive measure of an individual's true $HR_{\max}$; higher values have been observed during field training or competition than during laboratory testing (Semin et al. 2008). Equally, these data cannot determine whether the difference reflects incomplete attainment during CPET, TZM overestimation, or both. Validation against the highest heart rate obtained across repeated maximal laboratory and field efforts would be more informative. Model V_3 also exceeded CPET $vVO_{2\max}$ slightly ($0.37 \text{ km}\cdot\text{h}^{-1}$), in the same direction as the $HR_{\max}$ difference. $VO_{2\max}$, derived from V_3 with a fixed running cost, showed a small mean bias, but its individual limits of agreement were wider, partly because individual running economy is not represented; this warrants attention when an estimate is used to assess change in a single individual.

Estimation of maximum sprint speed

The sprint comparison extends the validation beyond variables measured in CPET. TZM estimated maximum running speed from the submaximal profile without using the subsequent 50-m sprint result in its fit. The strong association with measured

sprint speed ($R^2 = 0.98$), small mean bias, and mean absolute error of $0.40 \text{ km} \cdot \text{h}^{-1}$ support the model's ability to recover this outcome within the runners studied.

Maximum sprint speed has a distinct role in physiological profiling. Sprint performance depends on mechanical factors and interacting oxidative, glycolytic, and phosphagen contributions (Briand et al. 2025). In the 50-m sprint, the fastest 10-m splits were reached about 5–7 s after the start (Online Resource 2, Table S1), before glycolytic flux is expected to peak (Dunst and Meixner 2026), so the measured maximum speed reflects mainly alactic and neuromuscular capacity. The difference or ratio between maximum sprint speed and maximal aerobic speed is commonly described as the anaerobic speed reserve or speed reserve ratio. Studies of middle-distance and 400-m runners show that these measures help distinguish athletes with different sprint–endurance profiles (Sandford et al. 2019; Rappelt et al. 2025). The present result concerns estimation of maximum sprint speed, rather than validation of the full speed-reserve framework or prediction of race performance. Because sprint speed also depends on acceleration, neuromuscular capacity, and running mechanics, the accuracy observed here should be tested in sprinters, less-trained adults, and independent cohorts before generalizing beyond the sampled runners.

Endurance parameter E

The strong correspondence between model-derived E and E_r supports the TZM-predicted relationship among endurance, VT_2 speed, and maximum sprint speed. The comparison uses VT_2 and sprint measurements obtained independently of the submaximal model fit. However, their conversion to E_r follows the same model geometry used to define E . It therefore provides a test of that geometry, rather than validation of E against an independent physiological measure of endurance. The proportional bias is material: a small overall mean difference does not imply uniform agreement at low and high E values. Error-tolerant regression confirmed that E_r varies more across individuals than E (slope ≈ 1.27). Because E_r is derived from the ratio of measured sprint speed to CPET VT_2 speed, the slight compression of model V_2 relative to CPET VT_2 (slope 1.08) propagates into a wider spread of E_r . Alternatively, the endurance dependence of the $V_{\max}$ extension may be underestimated. Distinguishing these requires an independent cohort. The strong negative association between E and the sprint-to-pace ratio ($r = -0.88$) nevertheless shows that E carries individual information that a fixed ratio cannot.

Threshold position and the reserve extending toward sprint speed may reflect several physiological and mechanical characteristics. Evidence that glycolytic properties can influence metabolic thresholds independently of $VO_{2\max}$ offers one possible interpretation (Meixner et al. 2026; Quittmann 2026), but neither glycolytic flux nor muscle characteristics were measured here. At a given $VO_{2\max}$, cyclists with higher maximal glycolytic flux reach their lactate and ventilatory thresholds at lower power (Meixner et al. 2026). TZM expresses a similar pattern geometrically: low E places thresholds lower relative to $vVO_{2\max}$ and widens the reserve to maximum speed. A direct test would relate E to sprint-derived peak lactate accumulation rate. E also describes a baseline relationship among capacities; it should not be equated with durability, which concerns how physiological determinants change during prolonged exercise (Jones 2024; Jones and Kirby 2025). Direct comparisons with sustained performance, repeated assessments after fatiguing exercise, and independent metabolic measurements are needed to establish what E captures beyond its specified geometry.

Strengths and limitations

Separate submaximal, CPET, and sprint tests allowed TZM predictions to be compared with outcomes not supplied to the model fit, while reporting individual errors alongside correlations strengthened the evaluation. Limitations include modest and

outcome-dependent sample sizes, uncertainty in ventilatory-breakpoint placement, a fixed testing sequence, and restriction to individuals tested under controlled treadmill conditions. CPET HR_{peak} may not represent true HR_{max} , and sprint-derived maximum speed depends on effort and measurement protocol. The running-cost constant and the benchmark constants were derived in this cohort, and some model choices were informed by these data; external replication is therefore required. The drift-scaling factor ϕ was adjusted in about half of the participants, which adds flexibility to the exercise-phase fit; agreement did not differ between participants with and without this adjustment, but an objective, pre-specified criterion for its use should be established.

Although the measurements used to calculate E_r were independent of the submaximal fit, their transformation followed TZM geometry and therefore does not independently validate the physiological meaning of E . Test–retest reliability, external validity, and sensitivity to training-induced change remain to be established; accuracy across individuals does not necessarily imply an ability to detect small changes within an individual. The findings support further evaluation for repeated assessment but do not establish that TZM can replace CPET for all purposes, including direct gas-exchange measurement.

Conclusion

A single submaximal running and recovery test enabled TZM to estimate ventilatory thresholds, VO_{2max} , HR_{max} , and maximum sprint speed with strong correspondence to independent CPET and sprint measurements, with the clearest advantage over a pace-based estimate for intensities far from the tested pace. Estimated HR_{max} exceeded CPET HR_{peak} , a difference that may reflect incomplete attainment of true HR_{max} during CPET, model overestimation, or both. The correspondence between E and E_r calculated from independent threshold and sprint measurements supports the model-predicted endurance geometry and identifies E as a candidate measure of aerobic endurance. These findings support submaximal heart-rate kinetics as an integrated approach to individualized physiological assessment, while external validation and direct testing of the physiological meaning of E remain necessary.

349 **Data availability statement**

350 The original contributions presented in the study are included in the article/online resources, further inquiries can be directed
351 to the corresponding authors.

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361 **Author contributions**

362 AS conceived the study, prepared the ethics application, recruited participants and analyzed the data. AS and SSB performed
363 lab experiments and collected data. AS prepared the initial and final drafts of the manuscript. EJ and GJ supervised the study
364 and the manuscript preparation for publication. All authors read, revised, and approved the final version of the manuscript.

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367 **Ethics declarations**

368 **Conflict of interest**

369 AS is the founder and Chief Executive Officer of Driftline ehf., a company developing heart rate–based fitness and metabolic
370 tracking technologies. A PCT patent covering aspects of TrueZone analysis has been filed in Europe and USA. The remaining
371 authors declare no competing interest, nor commercial or financial relationships that could be construed as a potential conflict
372 of interest. The study was conducted under academic supervision (EJ and GJ) and approved by the relevant institutional
373 bioethics committee. The supervisors ensured that all study protocols, data analyses, and manuscript preparation were
374 conducted transparently and independently of commercial interests.

375 **Ethics approval**

376 The study was approved by the Icelandic Bioethics Committee (VSN-24-004) and thus conducted in accordance with the local
377 legislation and institutional requirements. The participants provided their written informed consent to participate in the study.
378 The study was conducted in accordance with the Declaration of Helsinki.

379 **Online Resources**

380 **Online Resource 1:** Supplementary methods for ventilatory-threshold identification and treadmill-speed correction.

381 **Online Resource 2:** Supplementary results, including descriptive statistics, representative model fits, and regression analyses.

382 **Online Resource 3:** Mathematical formulation of the TrueZone model, parameter fitting, and derivation of the endurance–
383 speed relationship.

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